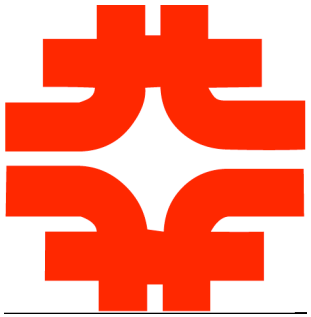
Measuring BAO with the 21 cm line of Hydrogen

John Marriner

April 18, 2009



Science Case

The Dark Energy Task Force (DETF) report highlighted 4 techniques to probe dark energy

- Type Ia supernovae
- Baryon Acoustic Oscillations
- Weak lensing
- Clusters

BAO phenomena

- Density fluctuations in the early universe propagate as sound waves.
- At the time of recombination the density fluctuations are frozen into the pattern of mass distribution in the universe.
- The distance travelled by the waves constitutes a "standard ruler" that can be used to determine cosmological parameters.
- Experimentally one measures the density function by measuring the distribution of galaxies.

BAO Observations

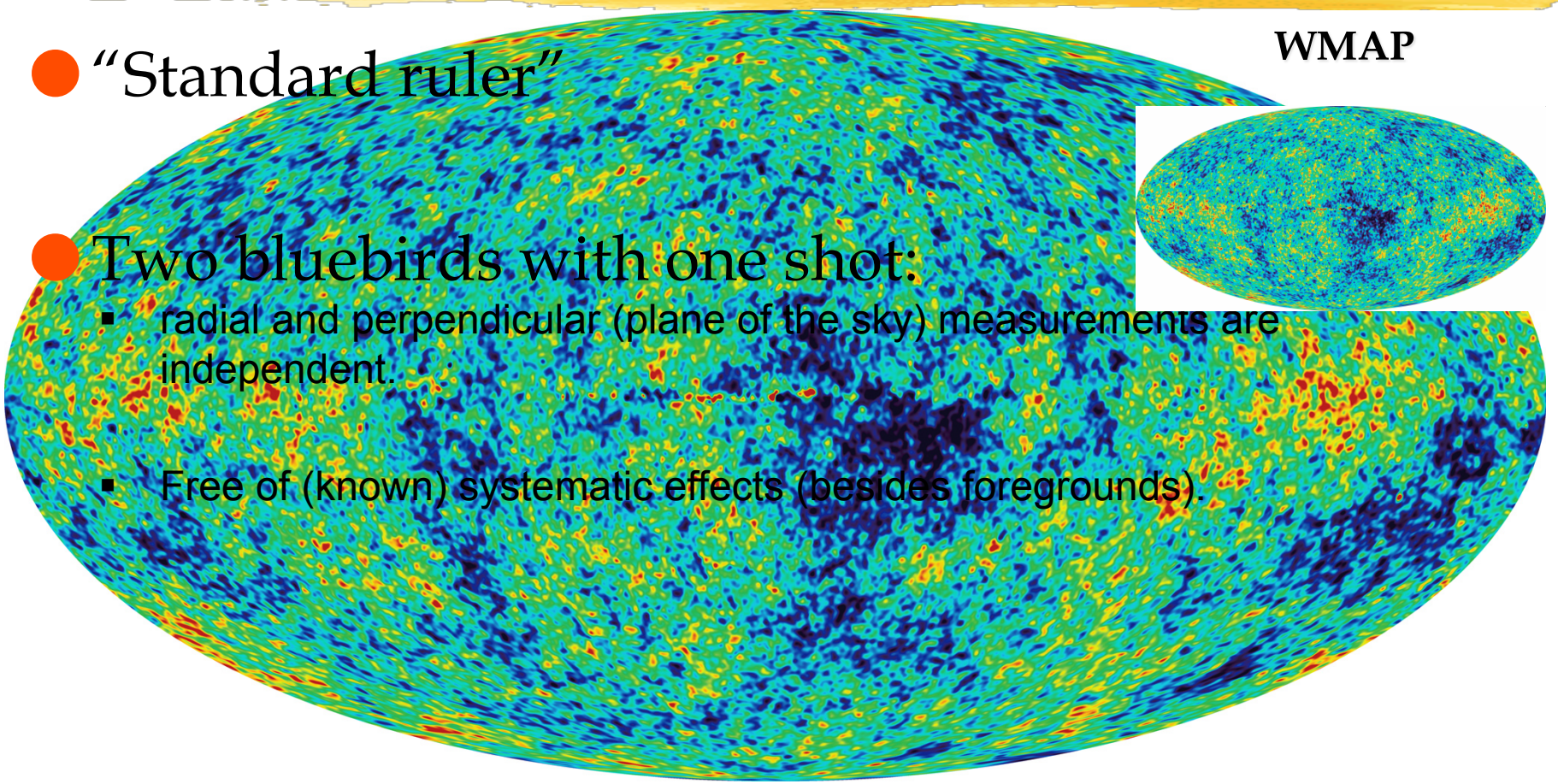
- BAO have been observed by SDSS.
- A number of future optical surveys (BOSS, DES, WFMOS, JDEM) are planned, some of which are in the construction phase.
- The use of the 21 cm line of hydrogen is a new approach that is complementary to optical surveys in sensitivity to bias and is able to probe to very high red shifts.
- A workshop is planned to discuss other science accessible to a wide field 21 cm survey.

21 cm line of Hydrogen

- Arises from the hyperfine transition in neutral hydrogen atoms.
- Is observed at 1.420 GHz in the radio spectrum for galaxies at a redshift of z=0.
- In the proposed 21 cm survey
  - The radio spectrum is dominated by "foregrounds"
  - Galaxies are not generally resolved (angular resolution of ~20 arc-min)
  - The 21 cm line is not generally resolved in frequency.

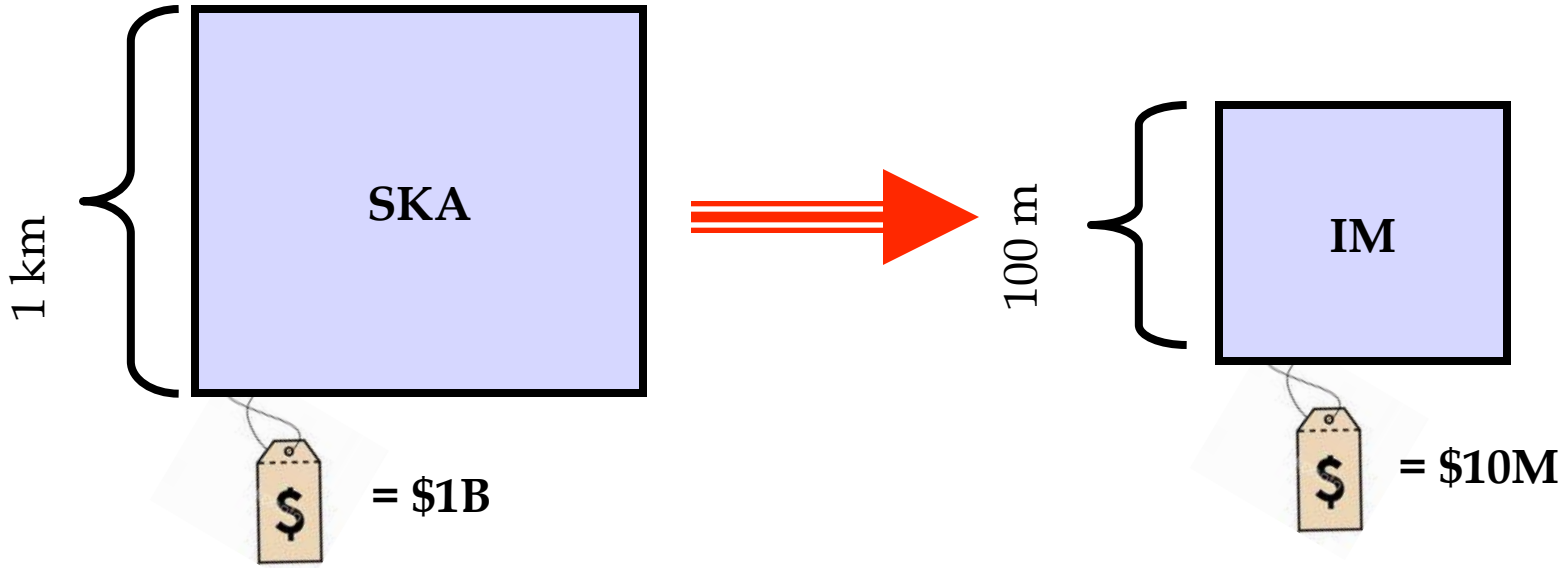
Baryon Acoustic Oscillations

- "Standard ruler"
- Two bluebirds with one shot:
  - radial and perpendicular (plane of the sky) measurements are independent.
  - Free of (known) systematic effects (besides foregrounds).



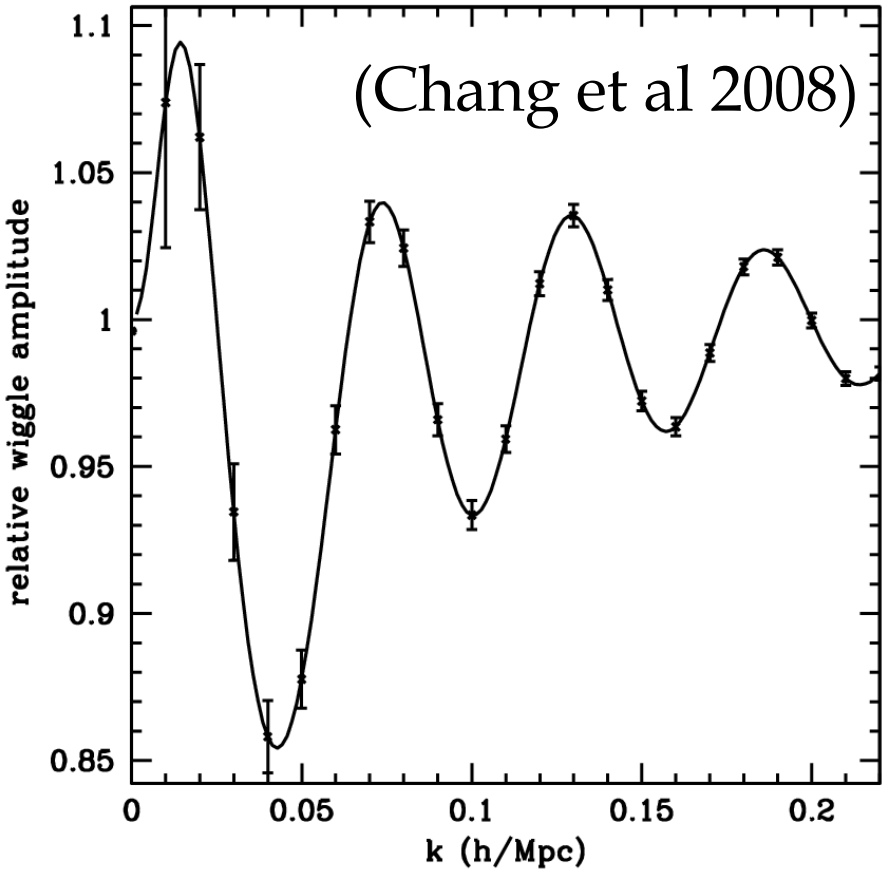
Intensity Mapping in 21cm

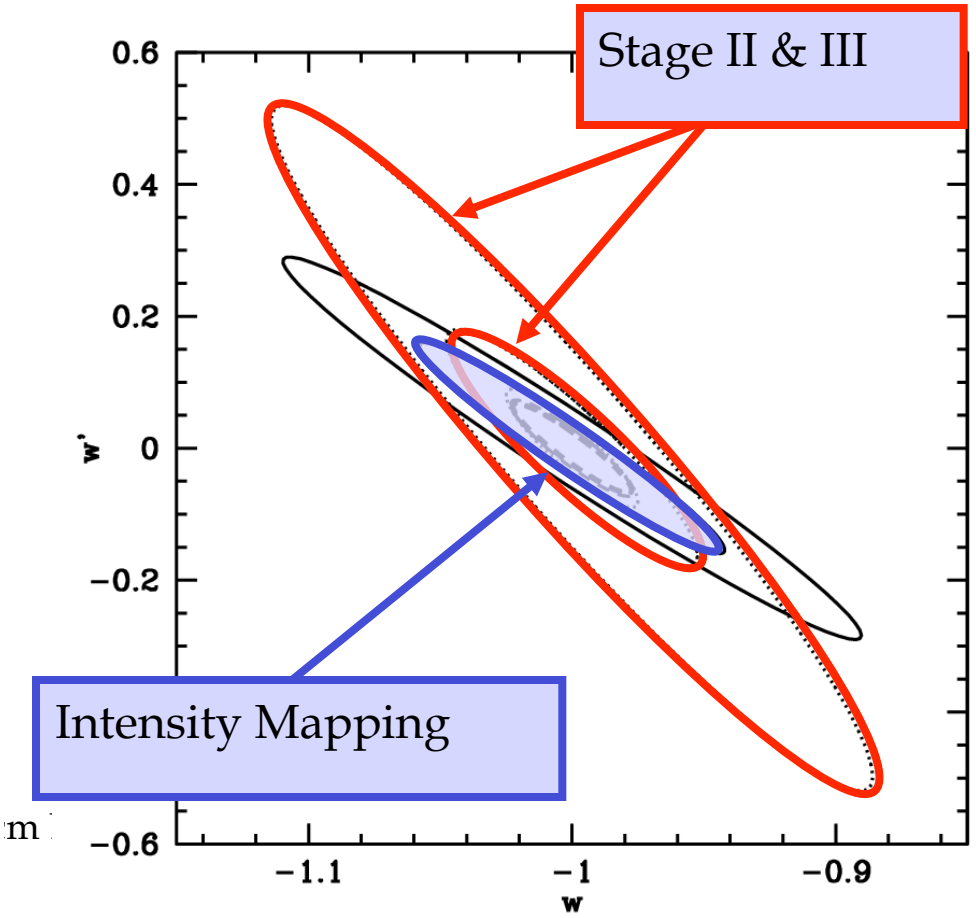
- The BAO spatial scale is 150 Mpc.
- At z=1 this size subtends 2.5 degrees.
- For λ=21cm this gives a telescope size of 10 m.



Accuracy of the Intensity Mapping Experiment

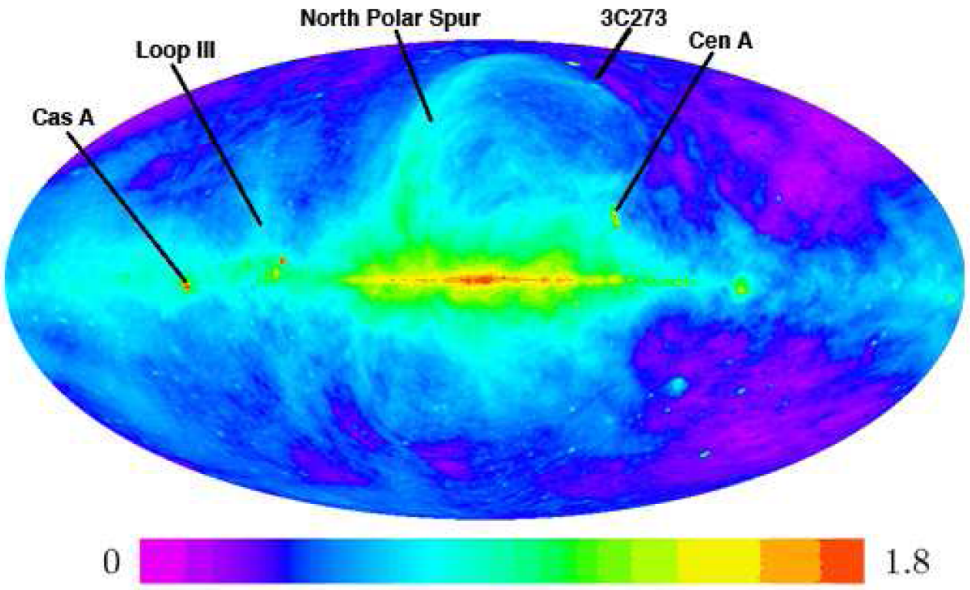
- IME can measure precisely at least 3 wiggles.





What Are We Paying For This Lunch?

- The crucial difficulty of this project is in the weakness of the signal relative to foregrounds:
  - Galactic synchrotron
  - External radio galaxies
  - Galactic free-free



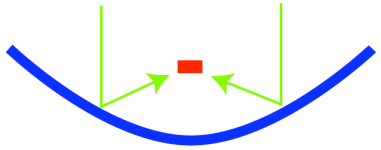
1 K **60 K**

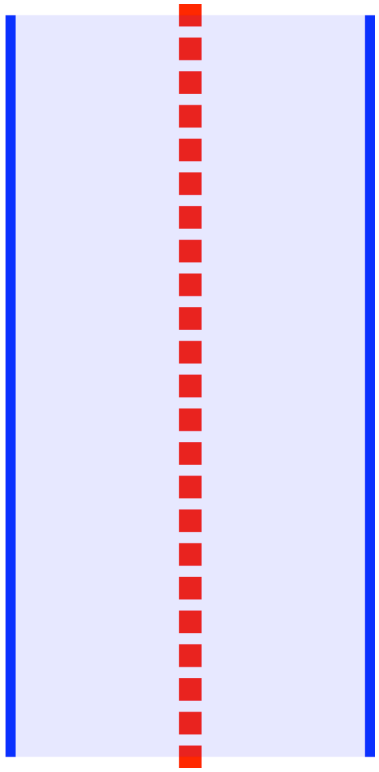
Some Numbers

- ☒ Foreground signal: 1- 10 degrees K
- ☒ Total 21cm signal: 300 μK
- ☒ Density variations ~3 μK
- ☒ BAO: 10% of that (0.3 μK)
- ☑ Foregrounds are smooth functions of frequency; they can be subtracted to reveal the BAO signal.
- ☑ Required level of sensitivity is achieved in "only" about 100 days of integration.

Concept

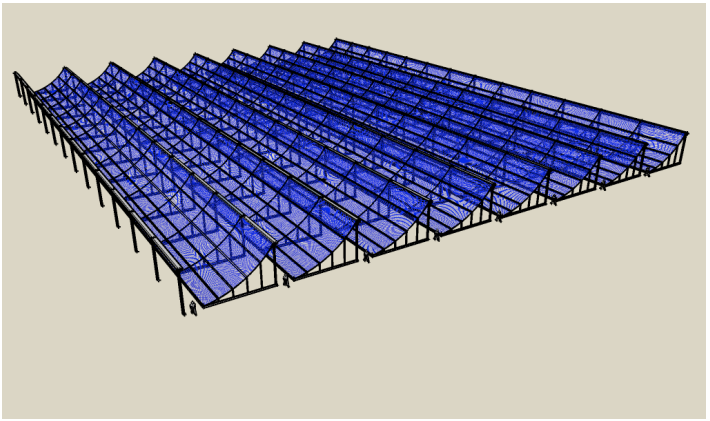
- Measure redshifted 21 cm H line 0.5<z<2 (about 500 MHz to 1000 MHz)
- Use paraboloid (a.k.a. cylindrical) dishes in N-S orientation.
- Array size ~100m x 100m
- Dense packing (critical sampling) ~10^4 channels
- Must be inexpensive

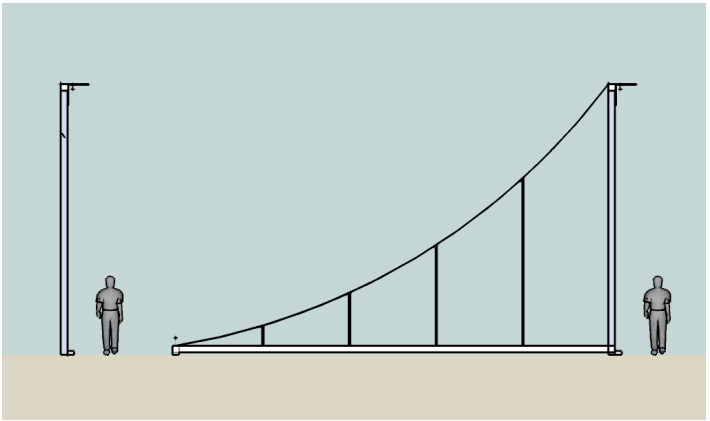




Antenna Array

- Reflecting shape is a tensioned wire mesh.
- Cylinder shape is a segment of a parabola.
- Cylinder height ~5 m.
- Cylinder width ~10 m.
- Array consists of 8 uniformly spaced cylinders.
- Feed line attached to pole/antenna support.





Why is FNAL interested?

- FCPA held a retreat in November 2007 to study future directions.
- A talk by Jeff Peterson (Carnegie-Mellon) inspired several of us to consider the feasibility of a 21 cm survey experiment.
- FNAL has significant expertise and keen interest in cosmology including BAO and CMB probes.
- FNAL has technical expertise relevant to the project.

Technical Capabilities at FNAL

- RF analog signal processing (accelerator applications).
- RF digital signal processing (accelerator applications).
- High speed parallel data processing (particle experiments)
- High speed data transport (particle experiments)
- Large astronomical data sets (SDSS)
- Project management & cost & schedule discipline

Decadal Survey White Paper

arXiv:0902.3091

21 cm Intensity Mapping

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The French Connection

Carnegie-Mellon test cylinders

References

- R. Ansari, et al., "Reconstruction of HI power spectra with radio-interferometers to study dark energy," arXiv: 0807.3967 (July 2008)
- Tegmark & Zaldarriaga, "The Fast Fourier Transform Telescope," arXiv:0805.4414v1 [astro-ph] (May 2008)
- Chang, Pen, Peterson, & McDonald, "Baryon Acoustic Oscillation Intensity Mapping as a Test of Dark Energy," arXiv:0709.3672v2 [astro-ph] (Jan 2008)
- Peterson & Bandura, "The Hubble Sphere Hydrogen Survey," arXiv:astro-ph/0606104v1 (June 2006)

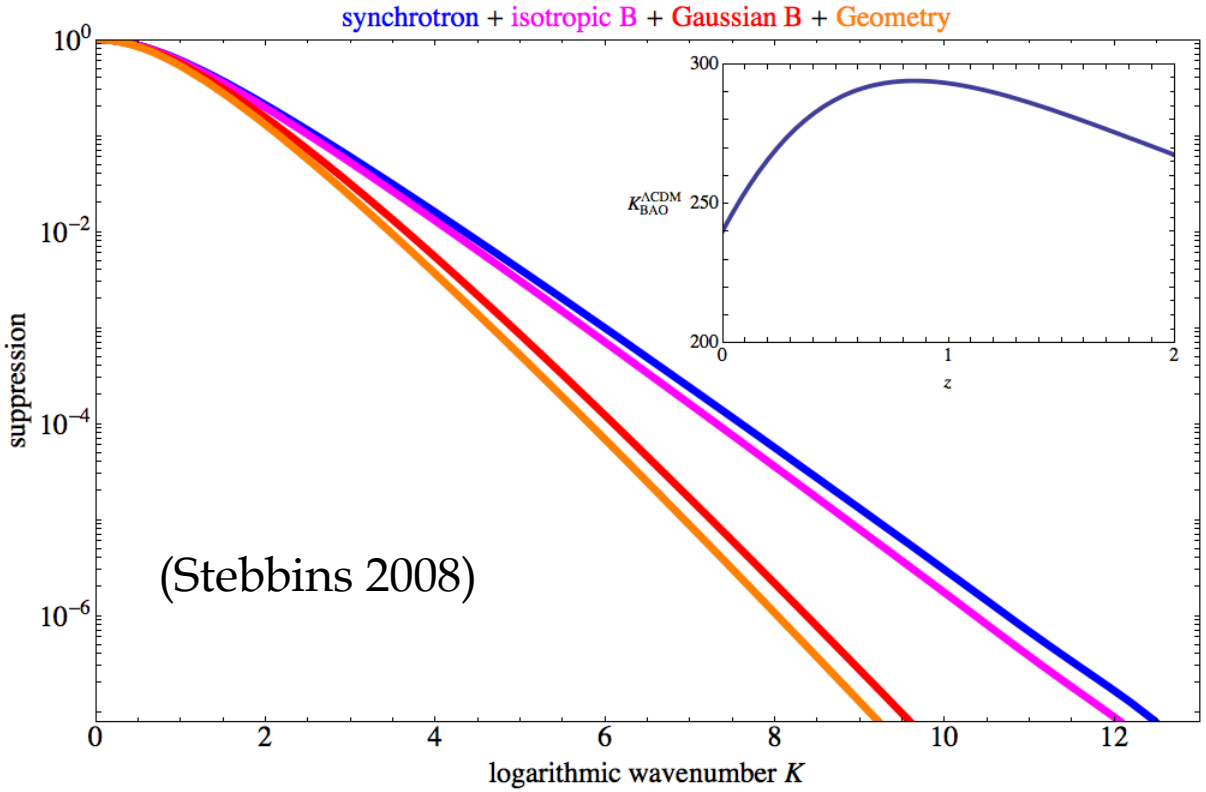
CRT Proposal Status

- Proposal to build the CRT in Morocco is pending. International collaborators include Carnegie-Mellon, Toronto, CEA, & FNAL.
- Proposal to build the CRT at Penticton, B.C. by a group of Canadian universities. At the moment the only non-Canadian participant is Peterson from Carnegie-Mellon.
- There are no pending requests to U.S. agencies for construction funds.

FNAL Activities

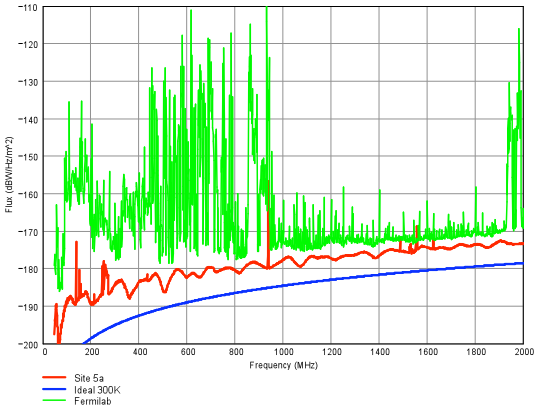
- Antenna design – McGinnis
- Simulation—Stoughton
  - BAO signal – Gneddin
  - Instrument response – Stoughton & Marriner
  - BAO analysis – Seo & Vallinotto
- Foreground characteristics & other grand thoughts--Stebbins
- Experimental measurement of foregrounds? – Scarpine

Fluctuations in the Synchrotron Spectrum

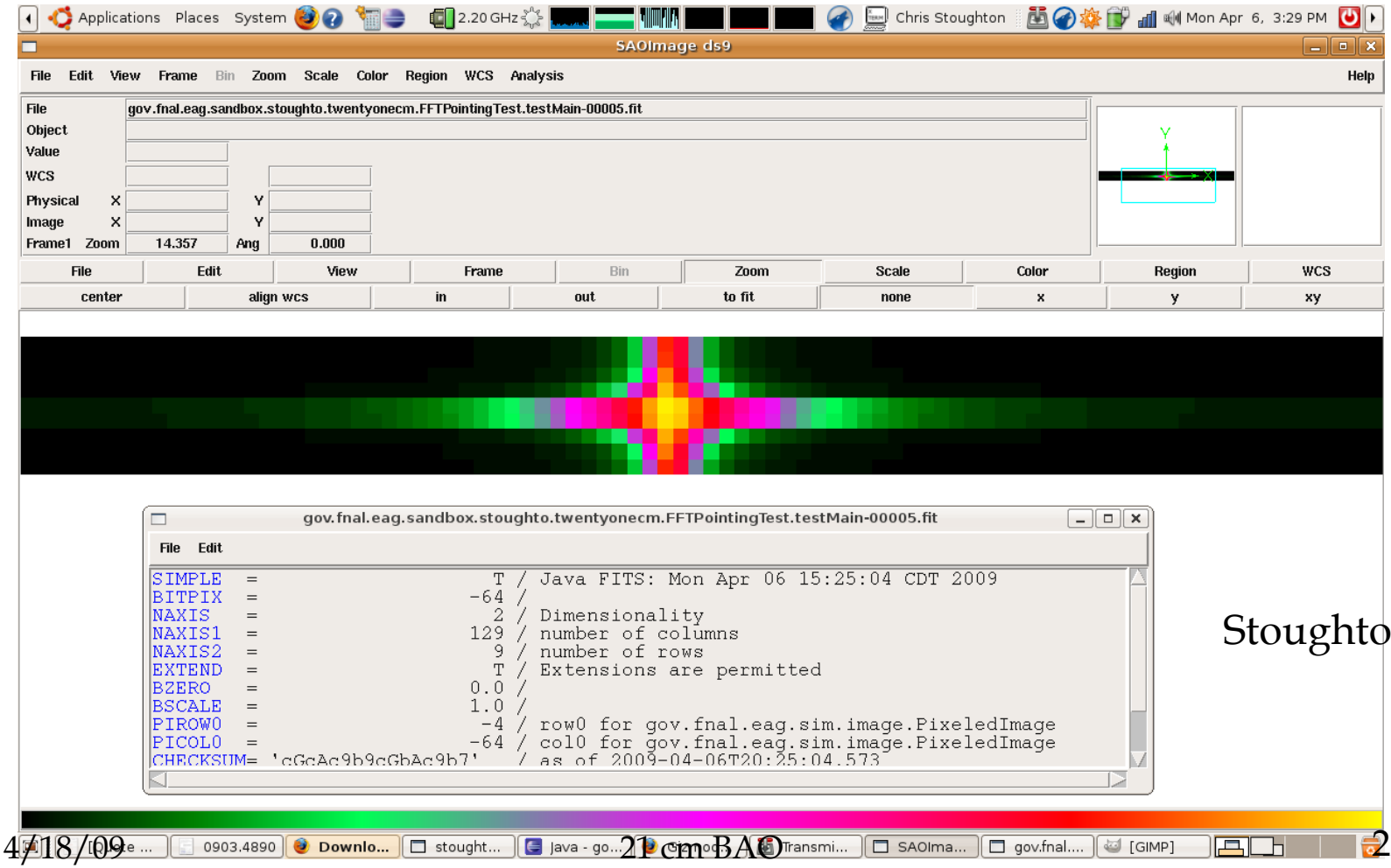


Smooth power spectra in the frequency domain (radial direction) are key to successful foreground subtractions.

Site Measurements



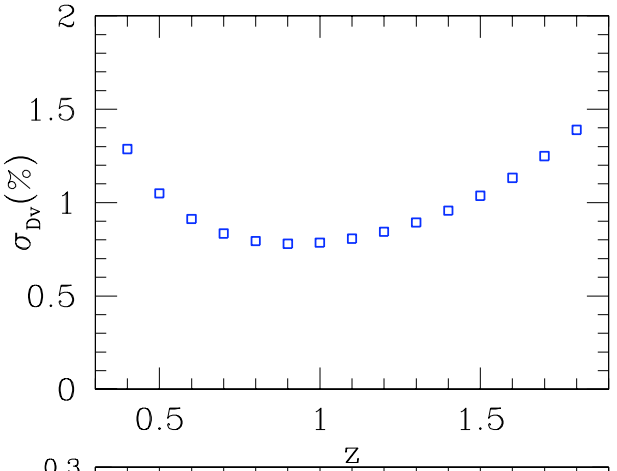
Simulated Telescope Response

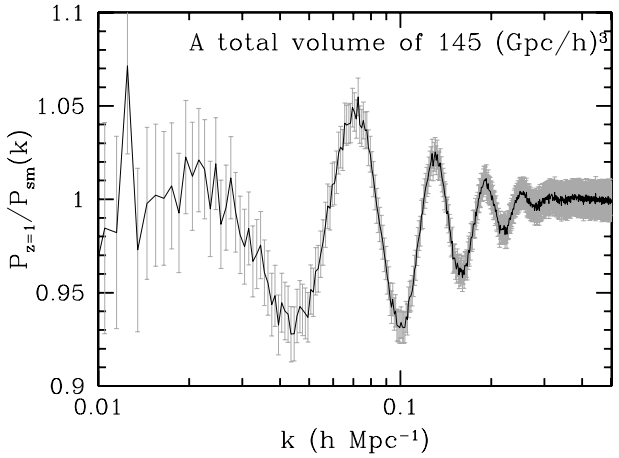


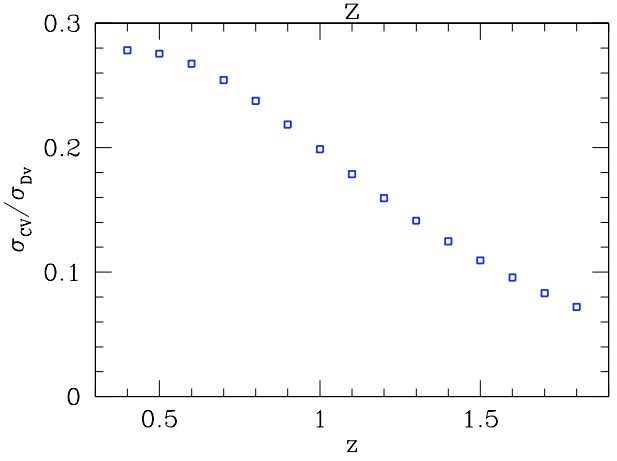
Stoughton, 2009

Sensitivity Calculations

Hee-Jong Seo
Work in Progress







Why Fermilab?

- Fundamental cosmology
- Critical expertise in r.f. and wide field surveys
- Project management and fabrication expertise

Risks

- We seem to be assured that the science will be interesting.
- The technical challenges are considerable.
- Collaboration & funding issues are still be sorted out.

Next Steps

- Continue R&D and produce a self-consistent design report.
- Seek support for FNAL-based portion of the effort.
- Build the collaboration